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Magnetic fields in our Galaxy: How much do we know? (II) Halo fields and the global field structure

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Abstract. I review the large scale global magnetic field structure of our Galaxy, using all information available for disk fields, halo fields and magnetic fields near the Galactic center (GC). Most of the knowledge was obtained from the rotation measures (RMs) of pulsars and extragalactic radio sources. In the local disk of our Galaxy, RM and dispersion measure (DM) data of nearby pulsars yield the strength of regular field as 1.8μG, with a pitch angle of about 8°, and a bisymmetric spiral structure. There are at least four, maybe five, field reversals from the Norma arm to the outskirts of our Galaxy. The regular fields are probably stronger in the interarm regions. The directions of regular magnetic fields are coherent along spiral arms over more than 10kpc. The regular fields get stronger with decreasing radius from the GC. In the thick disk or Galactic halo, large scale toroidal magnetic fields, with opposite field directions in the Southern and Northern Galaxy, have been revealed by the antisymmetric RM sky towards the inner Galaxy. This signature of the A0 dynamo-mode field structure is strengthened by the indication of a poloidal field of dipole form, that is the transition of the RM signs probably shifted from $l \sim 0^{\circ}$ to $l \sim +10^{\circ}$. The local vertical field is probably a part of this dipole field. The field structure of the A0 dynamo-mode strikingly continues towards the region near the GC. We predict that the direction of the dipole fields near the GC should point towards the Southern pole. In short, the magnetic fields in the Galactic disk have a bisymmetric spiral structure of primordial nature, while in the halo and near the GC the A0 dynamo seems to dominate, so that the fields consist of toroidal fields with opposite directions below and above the Galactic plane and poloidal fields of dipole form.

INTRODUCTION

The magnetic field structure in the Milky Way Galaxy is not yet fully known. It probably will never be observed completely, analogous to the situation of mapping the large scale structure of the universe. However, our Galaxy is a very special case for study, partly because we can see more “trees” though not the “forest”. One can observe many more details of the magnetic fields, and study their roles in star formation regions [1]. The details of local field structure and strength are very fundamental to understanding cosmic rays [2], especially those of high energy. The diverse polarized features observed in the diffuse radio emission [3, 4, 5, 6] are closely related to the small- and large-scale of magnetic fields. The fields are also important to the hydrostatic balance [7] and stability. While in the Galactic disk, the spiral structure is not yet clear, measuring the regular magnetic field structure could be an approach to mapping the Galaxy.

The major advantages of studying the magnetic field of our Galaxy are the fact that the Galaxy fills the sky and that a very number of pulsars and polarized extragalactic radio sources can be used as probes of the three dimensional magnetic field structure. These are unique to our Galaxy and extremely powerful for the halo field study. For the second largest galaxy in the sky, M31, there are only 21 bright polarized background radio sources[8].

Here I review the new progress obtained mainly in the last decade, and point to several earlier reviews (e.g. Sect.3 of [9], [10]) which clearly show the situation about 10 years ago. This is a companion paper for the review of observational facts of disk fields within a few kpc from the Sun [11]. This paper will focus on the field structure in the halo and near the Galactic center, with brief discussion of the disk fields so that the global field structure can be delineated.

MAGNETIC FIELDS IN THE GALACTIC DISK

Significant progress has been made in the last decade on the magnetic fields in the Galactic disk, mainly because of many pulsars newly discovered in the nearby half of the whole Galactic disk [12, 13, 14] and extensive observations of pulsar RMs [15, 16, 17]. Analyses of pulsar RM data [18, 16, 19, 17, 20] yield most definite key parameters of the regular magnetic field, namely the pitch angle of local fields, the field strength, and the field reversals.

Determining the local magnetic field was the main objective of measuring the polarization of star light. Using the largest data set of 7500 stars [21, 22], local magnetic fields were found to be concentrated in the spiral arms and directed along the axes of the arms, with a pitch angle of $p = -7.2^\circ \pm 4.1^\circ$. About a decade ago, a few dozen pulsar RMs were not enough to determine the field pitch angle more accurately than 10°. After Hamilton & Lyne obtained the RMs of 185 pulsars[15], Han & Qiao obtained the pitch angle $p = -8.2^\circ \pm 0.5^\circ$ from model-fitting to the data of carefully selected pulsars within 3 kpc[18]. The result was confirmed later using more pulsar RM data [19, 17], and is consistent with the value from optical data. Nowadays, there is no longer any doubt on the spiral feature of the local regular field, which has a pitch angle, $p = -8^\circ$, with a maximum uncertainty of 2°.

Talking about the field strength, we have to be aware of the difference between the total (rms) field strength, the strength of the regular field, the average field strength over a line of sight, and the maximum strength of the reversed field model. Total fields obviously are stronger in the arm regions, mainly contributed by random fields. That is about 5 μG in the vicinity of the Sun. However, regular fields are stronger in the interarm regions [18, 19]. The average field strengths *directly* determined from pulsar DM and RM are mostly in a range of $1 \sim 2\mu$G, with a maximum about 5μG (see Fig.1), suggesting a regular field of $1 \sim 2\mu$G and a random field about 5μG. These are exactly the values obtained by sophisticated analyses [23, 24, 18]. Note that the magnetic field energy stored in the random component is 3.7 times than the regular field [18], indicating that the random field always dominates. Our new measurements of magnetic field in the Norma arm[20] show that the regular fields themselves could be as strong as 5μG, indicating that the field strength probably increases smoothly towards the Galactic center.

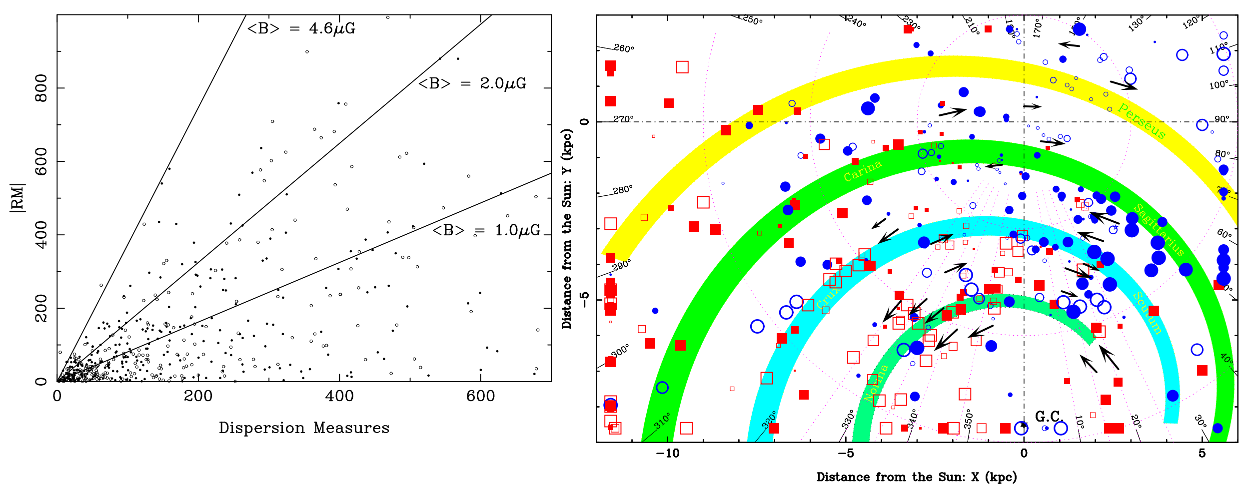

FIGURE 1. *Left:* Pulsar rotation measure values plotted against pulsar dispersion measure values, directly show the field strength averaged over the paths from pulsars to us. *Right:* The distribution of pulsar rotation measures projected onto the Galactic plane. Square symbols represent new measurements. Open symbols represent negative RM values. The field directions along the four spiral arms are indicated by arrows.

Pulsar rotation measures can tell the directions of the averaged field, in contrast to the orientation obtained from polarization of starlight or mapping at radio bands. The local regular magnetic field is pointing towards $l \sim 82^\circ$. There are at least four, maybe five, field reversals (see Fig.1) from the Norma arm to the outskirts of our Galaxy[20, 17, 19, 16, 18]. By comparison of the RM values of distant pulsars with those of extragalactic radio sources, at least one, probably two field reversals have been identified near and beyond the Perseus arm [25, 26, 17]. In the inner Galaxy, the fields first reverse their direction at about 0.2 kpc inside the solar ring, near the Carina-Sagittarius arm. The fields are reversed back again near or interior to the Crux-Scutum arm, as first shown by pulsar RM data [16]. New RM observations of more distant pulsars suggested that the fields near the Carina-Sagittarius arm and the Crux-Scutum arm are coherent in direction over more than 10 kpc along the spiral arms. From the most recent data we have identified the coherent counterclockwise fields near the Norma arm, indicating a third field reversal [20, 17].

Compared to that of external galaxies, the magnetic fields in the disk of our Galaxy is exotic because of these field reversals. Similar phenomena have not been observed in external galaxies [27]. A proper model to available data is the only way when astronomers have only the parts but like to understand the entire story. Three models were proposed for the global structure of magnetic fields in the disc of our Galaxy: the concentric ring model [24, 16], the axisymmetric spiral (ASS) model [28] and a bisymmetric spiral (BSS) [29, 30, 18, 19].

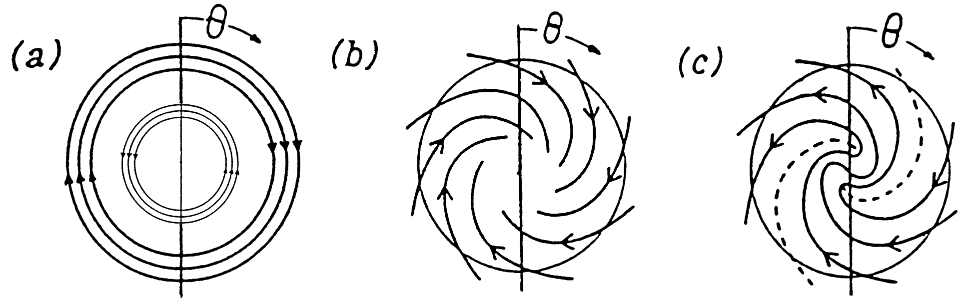

FIGURE 2. A sketch of three models for Galactic magnetic fields (modified from [31]), namely, (a) the concentric ring model, (b) the axi-symmetric spiral model, and (c) the bi-symmetric spiral model.

Only the concentric-ring model [24, 16] has a pitch angle of zero but the observed pitch angle of fields (see above) argues for a spiral form of the fields. Nevertheless, this model allows the fields to be reversed in different ranges of Galacto-radius, so this model explain the RM data for the zero-order of approximation. In the ASS model [28], the reversed field occurs only in the range of Galacto radius from 5 to 8 kpc. No field reversals are allowed beyond 8 kpc from the GC center or within 5 kpc of the GC. Field reversals beyond the solar circle or interior to the Crux-Scutum arm are difficult to reconcile with this model. The spiral nature of the regular field and the field reversals strongly support the BSS model for the disk fields in our Galaxy. Model fitting to available pulsar RM data [18, 19] have confirmed this conclusion.

Although only the BSS model has survived confrontation with RM data and star polarization data, it may be worth reminding that, though the model fits the available data, it could fail to fit data from these part of the disk as yet unexplored. There are two possibilities for farther tests of the model. One is to check closely the coherence of field directions; the other is to determine the fields in more distant regions. The essential step for both avenues is to obtain more pulsar RM data in the distant parts of the galactic disk.

MAGNETIC FIELDS IN THE GALACTIC HALO

As was shown by previous radio background observations, our Galaxy consists of two components[32], a thin disk and a thick disk. The magnetic field in the thin disk is more dominated by the spiral structure, as we discussed above. The thick disk has a scale height of 1.5 kpc near the solar circle [29, 18]. We refer to the thick disk, together with the more extended component, as the Galactic halo. The magnetic fields in the thin disk diffuse into the halo, as shown by the spurs or plumes emerging from the Galactic plane [33, 34] and as needed by dynamo actions.

Our Galaxy is the largest visual galaxy in the sky, and the RMs of extragalactic radio sources (EGRS) and pulsars are the best probes for the halo field. Our Galaxy provides a unique opportunity to study halo field structure, on either small or large scales. However, the RM sky has many features [29] related to local high-latitude phenomena, such as, the North Polar Spur region (Loop I), Region A (loop II), both of which are probably superbubbles or supernova remnants. Faint large-scale H_α filaments sometimes also affect the RM distribution [17]. Halo fields have not been well studied well, mainly because of these dominant local features.

After carefully filtering out deviant points, we found the antisymmetry of the rotation measure sky in the *inner* Galaxy[35]. Such a highly symmetric pattern could not be produced by just the coincidence of many local perturbations, instead, it is of large, probably galactic, scale. Such an antisymmetric sky suggests a magnetic field in the halo with opposite directions in the northern and southern Galactic hemispheres. We noticed later that Andreasyan & Makarov independently made a similar suggestion[36]. A very important fact is that such an antisymmetry only occurs at high latitudes for the inner part of the Galaxy, indicating that it is related to the field structure mainly in the Galactic halo. The field structure so revealed is amazingly consistent with that produced by an A0 dynamo. Together with the

vertical field near the Galactic center (see below), we believe that an A0-mode dynamo is operating in the Galactic halo. This is the first time that a dynamo mode has been identified on a galactic scale.

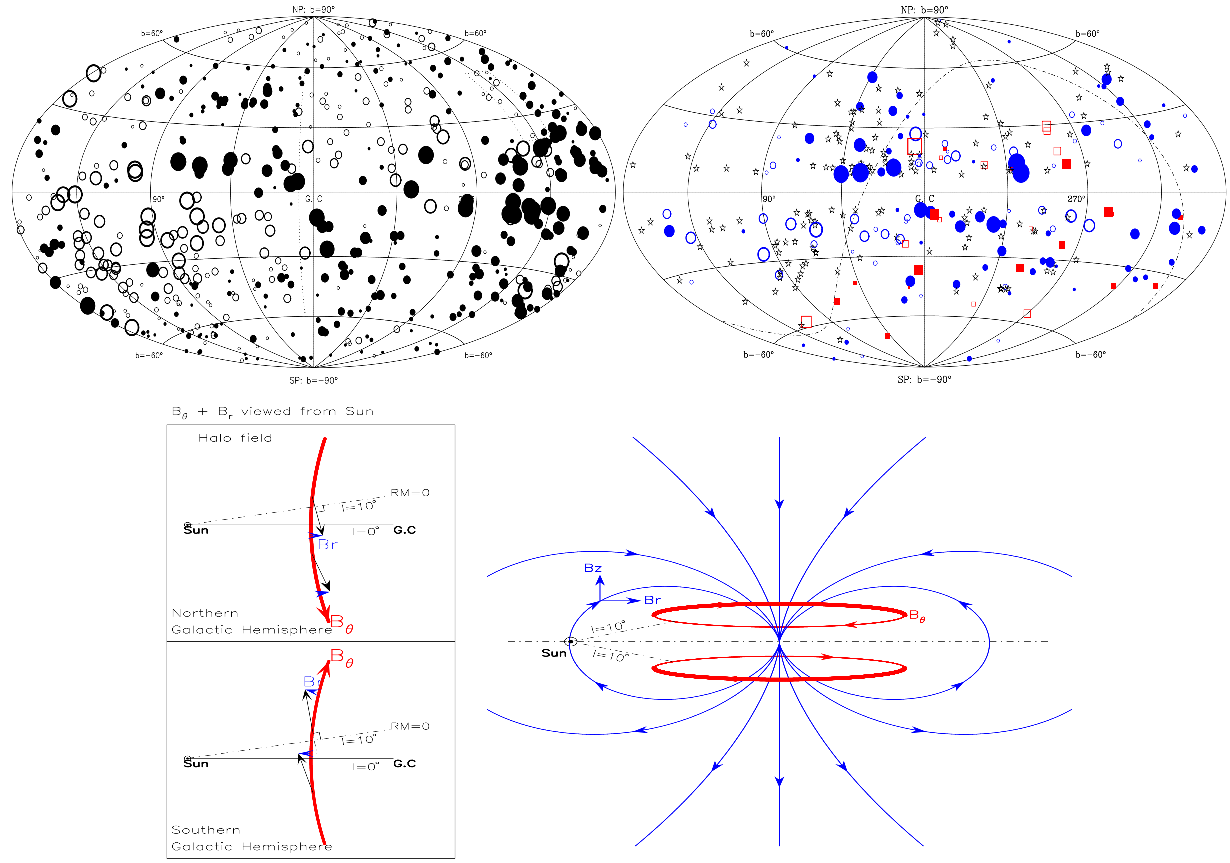

FIGURE 3. The antisymmetric rotation measure sky of extragalactic radio sources (*upper left*) and pulsars (*upper right*) directly indicates the reversed direction of the azimuthal magnetic fields in the southern and northern hemisphere of our Galaxy. The filled symbols represent positive RMs, indicating the averaged field towards us. The effect of the dipole field on the longitude transition of RM signs (*lower left*) and the magnetic field configuration of an A0-mode dynamo (*lower right*) are shown for comparison.

Two facts further support the argument for the dynamo origin of the antisymmetric rotation measures. One is the local vertical fields. After all local perturbations were discounted, we found that the vertical fields have a strength of 0.2∼0.3 μG and point from the South Galactic pole to the North [18, 17]. If this is a part of the dipole field expected from the A0 mode dynamo, then the longitude transition of RM signs should be slightly shifted from $l \sim 0°$ to $l \sim$ a few degrees, depending to the strengths of the dipole fields and the toroidal fields. The halo toroidal fields have a strength of about 1 μG [17]. The transition shift, though marginally shown by the available RM data of extragalactic radio sources and pulsars, was first noticed by Han et al. in 1999 [17]. We understand that this second fact needs more data to confirm, which we are currently working on.

In short, the RM sky demonstrates an A0 dynamo acting in the halo, producing azimuthal fields with opposite directions in the southern and northern galactic hemispheres and also dipole fields. All pieces of evidence are nicely consistent for these field components of the A0-mode dynamo field structure. Computer simulation of the toroidal and dipole fields, together with the electron distribution model[37] have confirmed all these features.

MAGNETIC FIELDS NEAR THE GALACTIC CENTER

Two aspects of the magnetic fields near the Galactic center should be discussed – first how the disk fields continue towards the center, and second, the possible presence of poloidal fields and toroidal fields there and any possible connections with the fields in the Galactic halo. On the continuation of disk fields, there is a knowledge gap to fill. We

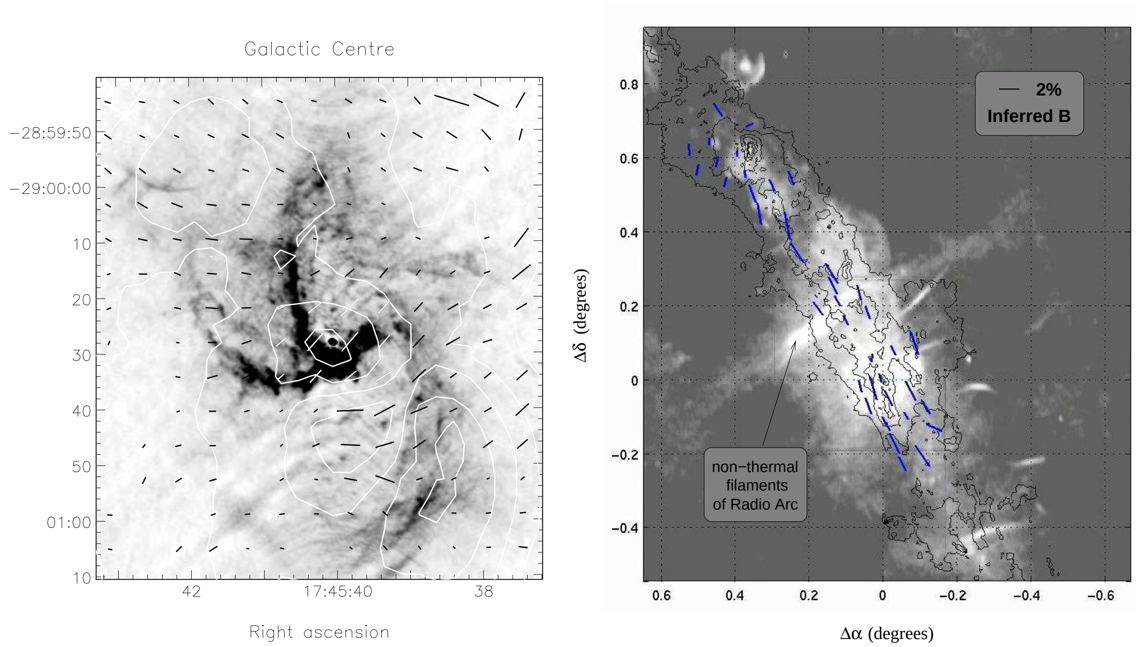

FIGURE 4. The diverse structure of radio emission near the Galactic center at 3.6cm (*left*) from [41] and 90cm (*right*) from [42]. Overlaid are the polarization observations at sub-millimeter in [43, 38]. The toroidal fields parallel to the Galactic plane (*right*) are clearly detected in the central molecular zone of 170 pc $\times$ 30 pc.

have only recently determined the field structure near the Norma arm and have no idea at all about the fields interior to this arm. It is not clear whether the strong magnetic fields observed in the central molecular zone [38, 39] are continued and connected to the large scale fields in the disk. It is the case for the nearby galaxy NGC 2997[40].

As a matter of fact, recognition of the dipole fields in the Galactic halo is fundamentally important. The magnetic fields of the dipole in the Galactic center then must be very strong (see Fig. 3) and should show many features. The filaments[44], plumes [34] and even threads [45] near the Galactic center all exactly reflect these strong dipole fields. They are the locally illuminated flux tubes in large-scale pervasive fields! Their locations, high linear polarization of 50% to 70% [45], and their curvatures, as well as their perpendicularity to the Galactic plane, all suggest the dipole nature of the poloidal field structure. The strength of the fields should of the order of mG [46]. As hinted by the direction of the local vertical fields, I predict that the dipole fields in the Galactic center then should be directed from the Northern pole to the Southern pole.

As well as the poloidal fields, Zeeman splitting [47] and polarization observations at sub-millimeter wavelength [39, 38] have revealed strong toroidal magnetic fields of 2 – 4 mG in the central molecular zone (see Fig. 4). Nova et al. found some evidence for the directions of these toroidal fields [38], exactly the same field configuration as we obtained for the halo field (see Fig. 3). This has led us to believe that the A0 dynamo probably is working from the GC to the halo.

GLOBAL STRUCTURE OF GALACTIC MAGNETIC FIELDS

In the last decade, knowledge of the magnetic field structure of our Galaxy has improved in many aspects through efforts in determining pulsar RMs and mapping near the Galactic center. However, the story is far from complete. Using the presently available information, we can conclude that our Galaxy has such an odd symmetry of the toroidal and poloidal fields in the Galactic halo and near the Galactic center, showing that the dynamo is really working through the inductive effects of fluid motions in the interstellar medium. However, bi-symmetric spiral magnetic fields in the Galactic disk suggest that the disk keeps some kind of memory of the field reversals from seed fields or the primordial fields. For any modeling to understand the origin of cosmic rays, both the large scale field in the disk and the halo should be considered. Polarization observations of background radiation can directly show the connections of large-scale disk fields to halo fields.

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